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ABSTRACT

This is one of five panel reports that have been prepared as part of the first phase of Project 2061, a long-term, multipurpose undertaking of the American Association for the Advancement of Science designed to help reform science, mathematics, and technology education in the United States. Major sections included are: (1) "Rationale"; (2) "A Conceptual Framework for Biology"; (3) "Human Biology" (discussing the human organism and its life cycle); (4) "The Evolution of Diverse Life-Forms"; (5) "Environmental Biology" (discussing the role of green plants and the ecosystem); and (6) "Human Ecology" (dealing with photosynthesis, recycling, pollution, and sustainable agriculture). The members of the panel and consultants are listed. (YP)

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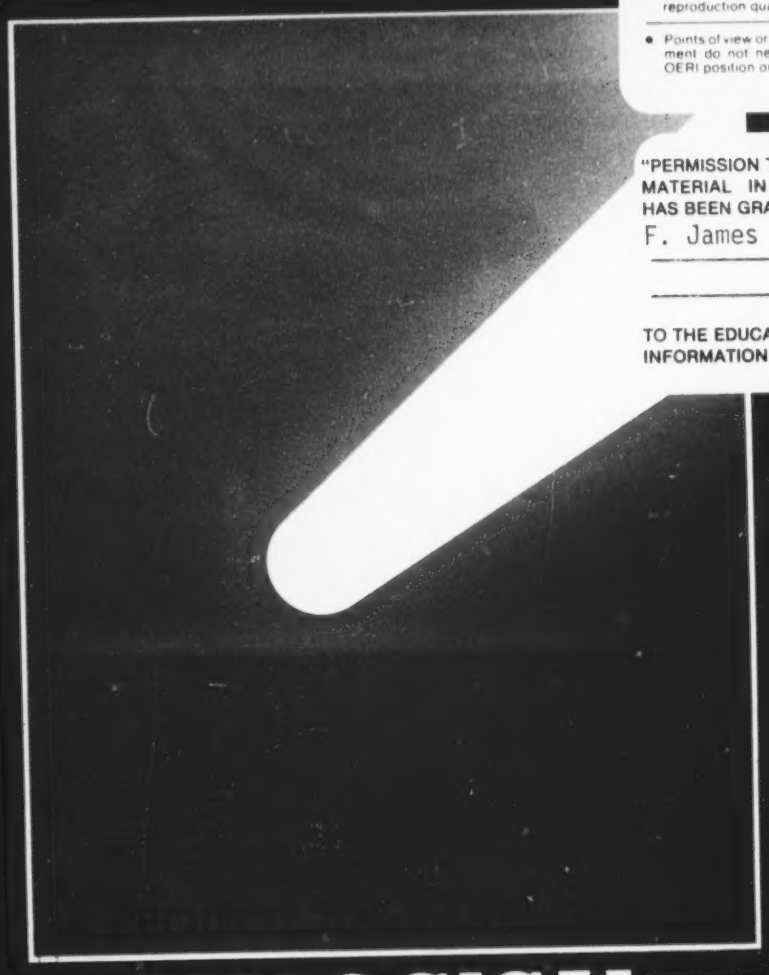

BIOLOGICAL AND HEALTH SCIENCES

SE 050 707

AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

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BIOLOGICAL AND HEALTH SCIENCES

REPORT OF THE
PROJECT 2061 PHASE I
BIOLOGICAL AND HEALTH
SCIENCES PANEL

by Mary Clark

AMERICAN ASSOCIATION
FOR THE ADVANCEMENT OF SCIENCE

1989

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Founded in 1848, the American Association for the Advancement of Science is the world's leading general scientific society, with more than 132,000 individual members and nearly 300 affiliated scientific and engineering societies and academies of science. The AAAS engages in a variety of activities to advance science and human progress. To help meet these goals, the AAAS has a diversified agenda of programs bearing on science and technology policy; the responsibilities and human rights of scientists; intergovernmental relations in science; the public's understanding of science; science education; international cooperation in science and engineering; and opportunities in science and engineering for women, minorities, and people with disabilities. The AAAS also publishes *Science*, a weekly journal for professionals, and *Science Books & Films*, a review magazine for schools and libraries.

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CONTENTS

Page

ACKNOWLEDGMENTS iii

PHASE I BIOLOGICAL AND HEALTH SCIENCES PANEL v

FOREWORD by F. James Rutherford, Project Director, Project 2061 vii

PREFACE by Helen M. Ranney, Chair, Biological and Health Sciences Panel xi

SECTION 1: RATIONALE 1

SECTION 2: A CONCEPTUAL FRAMEWORK FOR BIOLOGY 3

SECTION 3: HUMAN BIOLOGY 7

How Does the Human Organism Work and What Does It Take to Keep It Healthy? 7
From Conception to Death, What Are the Main Features of the Biological Life Cycle of Human Beings? 11

SECTION 4: THE EVOLUTION OF DIVERSE LIFE-FORMS 15

How Are Humans Like and Unlike Other Living Organisms? 15
How Do New Species Arise? 17

SECTION 5: ENVIRONMENTAL BIOLOGY 21

How Do Green Plants Feed Earth's Inhabitants? 22
What Determines the Productivity of an Ecosystem? 23
Why Are Most Natural Ecosystems Fairly Stable Over Long Periods of Time? 23

SECTION 6: HUMAN ECOLOGY 25

How Is the Continued Sustainability of the Ecosystems on Which We Depend Related to the Amount of Available Energy—Over and Above the Sunlight They Need for Photosynthesis? 25
By What Processes Are Resources Recycled? 26
How Does Accumulating Pollution Affect Humankind's Future? 27
What Ecological Considerations Are Necessary for a Sustainable Agriculture? 28

SECTION 7: CONCLUSION 31

APPENDIX: BIOLOGICAL AND HEALTH SCIENCES PANEL CONSULTANTS 33

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On behalf of the Board of Directors of the American Association for the Advancement of Science, I wish to acknowledge with gratitude the many useful contributions made by the members of the Phase I Biological and Health Sciences Panel to the first stage of Project 2061.

The nine panel members were most generous with their time and efforts over a two-year period in developing their response—as presented in this report—to the complex question of what young people should know about the biological and health sciences by the time they complete their high school education. The board is also very grateful to Helen M. Ranney, who chaired the panel, and to Mary Clark, who wrote the panel's report.

During this essential first stage of Project 2061, the Biological and Health Sciences Panel was one of five scientific panels charged by the AAAS with developing independent reports on five basic subject-matter areas. At the same time, the Project 2061 staff—in conjunction with the National Council on Science and Technology Education—was preparing a separate overview report—*Science for All Americans*—that was able to draw on the conclusions reached by the individual panels.

We also want to extend our thanks to the many people who assisted the Biological and Health Sciences Panel in the course of its deliberations—the consultants, the national council members and other reviewers, and the Project 2061 staff.

Finally, it is appropriate to note that Project 2061 is indebted to the Carnegie Corporation of New York and the Andrew W. Mellon Foundation for their overall and ongoing support of our various Phase I efforts.

Sheila Widnall
Chair, Board of Directors, American Association for the Advancement of Science

PHASE I BIOLOGICAL AND HEALTH SCIENCES PANEL

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Panel Staff: Jan Yaffe, Psychotherapist (San Diego)

FOREWORD

This report is one of five prepared by scientific panels as part of Phase I of Project 2061. Each of the panel reports stands alone as an independent statement of learning goals in a particular domain. In addition, the reports contributed to *Science for All Americans*, a Phase I report that cuts across all of science, mathematics, and technology.

The work of the Biological and Health Sciences Panel was to reflect on all aspects of biology and health—their nature, principles, history, future directions, social dimensions, and relation to the other sciences and technology—and to produce a set of recommendations on what knowledge and skills are needed for literacy in those domains (as part of general scientific literacy). The other panels focused in a similar way on mathematics, the physical and information sciences and engineering, the social and behavioral sciences, and technology.

In considering this report, it is helpful to see it in the context of Project 2061 and to be aware of the manner in which it was generated.

The American Association for the Advancement of Science initiated Project 2061 in 1985, a year when Comet Halley happened to be in the earth's vicinity. That coincidence prompted the project's name, for it was realized that the children who would live to see the return of the comet in 2061 would soon be starting their school years. The project was motivated by a concern that many share for the inadequate education those young Americans will receive unless there are major reforms in science, mathematics, and technology education.

Scientific literacy—which embraces science, mathematics, and technology—has emerged as a central goal of education. Yet the fact is that general scientific literacy eludes us in the United States. A cascade of recent studies has made it abundantly clear that by national standards and world norms, U.S. education is failing too many students—and hence the nation. The nation has yet to act decisively enough in preparing young people—especially the minority children on whom the nation's future is coming to depend—for a world that continues to change radically in response to the rapid growth of scientific knowledge and technological power.

Believing that America has no more urgent priority than the reform of education in science, mathematics, and technology, the AAAS has committed itself, through Project 2061 and other activities, to helping the nation achieve significant and lasting educational change. Because the work of Project 2061 is expected to last a decade or longer, it has been organized into three phases.

Phase I of the project has established a conceptual base for reform by defining the knowledge, skills, and attitudes all students should acquire as a consequence of their total school experience from kindergarten through high school. That conceptual base

consists of recommendations presented in *Science for All Americans* and the five panel reports.

In Phase II of Project 2061, now under way, teams of educators and scientists are transforming these reports into blueprints for action. The main purpose of the second phase of the project is to produce a variety of alternative curriculum models that school districts and states can use as they undertake to reform the teaching of science, mathematics, and technology. Phase II will also specify the characteristics of reforms needed in other areas to make it possible for the new curricula to work: teacher education, testing policies and practices, new materials and modern technologies, the organization of schooling, state and local policies, and research.

In Phase III, the project will collaborate with scientific societies, educational associations and institutions, and other groups involved in the reform of science, mathematics, and technology education, in a nationwide effort to turn the Phase II blueprints into educational practice.

Each of the five panels was composed of 8 to 10 scientists, mathematicians, engineers, physicians, and others known to be accomplished in their fields and disciplines and to be fully conversant with the role of science, mathematics, and technology in the lives of people. The panelists were different from one another in many respects, including their areas of specialization, institutional affiliations, views of science and education, and personal characteristics. What made it possible to capitalize on the rich diversity among the panelists was what they had in common—open minds and a willingness to explore deeply the questions put to them.

The basic question put to the Biological and Health Sciences Panel was: What is the biological and health sciences component of scientific literacy? Answering this question—difficult enough in itself—was made more so by the conditions, or ground rules, set by Project 2061. Abbreviated here, these were:

- ***Focus on scientific significance***. Identify only those concepts and skills that are of surpassing scientific importance—those that can serve as a foundation for a lifetime of individual growth.

- ***Apply considerations of human significance***. Of the knowledge and skills that meet the criterion of scientific significance, select those that are most likely to prepare students to live interesting and responsible lives. Individual growth and satisfaction need to be considered, as well as the needs of a democratic society in a competitive world.

- ***Begin with a clean slate***. Justify all recommendations without regard to the content of today's curricula, textbooks, state and school district requirements, achievement tests, or college entrance examinations.

- ***Ignore the limitations of present-day education***. Assume that it will be possible to do whatever it may take—design new curricula and learning materials, prepare teachers, reorganize the schools, set policies, or locate resources—to achieve desired learning outcomes.

- ***Identify only a small core of essential knowledge and skills.*** Do not call on the schools to cover more and more material, but instead recommend a set of learning goals that will allow them to concentrate on teaching less and on doing it better.

- ***Keep in mind the target population—all students.*** Propose a common core of learning in the biological and health sciences that can serve as part of the educational foundation of all students, regardless of sex, race, academic talent, or life goals.

Taking these ground rules into account, the members of the Biological and Health Sciences Panel met frequently over a period of nearly two years to present and debate ideas and to consider the suggestions of consultants. The panel members prepared working papers and revised them in response to the criticisms of reviewers. This process—which also included meetings with the chairs of other panels—led to the preparation of this report.

The task ahead for the United States is to build a new system of education that will ensure that all of our young people become literate in science, mathematics, and technology. The job will not be achieved easily or quickly, and no report or set of reports can alter that. I believe, however, that this report on scientific literacy in the biological and health sciences, along with the other panel reports and *Science for All Americans*, can help clarify the goals of elementary and secondary education and in that way contribute significantly to the reform movement.

F. James Rutherford
Project Director, Project 2061

PREFACE

The Biological and Health Sciences Panel was responsible for developing some concepts of biology, beginning with natural history and spanning molecular and cellular biology, human health (and physiology), and ecology. In the final report, the concepts of human health form a separate chapter; in many of the panel discussions, however, topics in human health were interwoven with relevant biological subjects.

The panel members had widely differing areas of expertise but a common interest in education. One particular point is worth mentioning here: In their discussions, the panel members often referred to, but never defined, the idea that schooling and education are not the same. We observed, for example, that many agencies besides the schools are involved in education, and if the scientific knowledge of all Americans is to be greatly improved, education outside the schoolroom must also be improved—perhaps even more than that within it.

We are grateful to our consultants, each of whom spent several Saturday hours with us. Jared Diamond of the University of California, Los Angeles, discussed population biology and ecology, and Donald Rains of the University of California, Davis, talked with us about agriculture. Two additional consultants, Jean Lindsley and Phoebe Roeder, enlightened us about current education programs in biology in the public and private high schools of the San Diego area. Michael Criqui of the Department of Community/Family Medicine at the University of California, San Diego, led a discussion of the issues involved in preventive medicine and epidemiology.

The views of the panel members on the science content of American education differed a good deal at the beginning and at the end of the panel discussions. It became evident that different reports could be prepared to represent the differing emphasis of individual panel members on molecular and cellular biology or on environmental issues and ecology. Eventually, though, it was decided that the approach of Mary Clark, a panel member and gifted writer on topics in biology and education in biology, was best suited to the purpose of this endeavor.

The members of the panel are indebted to Mary Clark and to Project Director F. James Rutherford and the staff of Project 2061 for their unflagging endeavors to complete this phase of the project.

Helen M. Ranney
Chair, Biological and Health Sciences Panel

SECTION 1

RATIONALE

Among the sciences, none is perhaps as naturally attractive as biology. All of us are curious about ourselves and about other forms of life in which we find greater or lesser similarities to ourselves. Yet, for the average American today, knowledge of the living world is badly distorted and frequently wrong. This situation comes about for two reasons. First, there is a lack of proper science education in homes and schools; such education should teach that methods of testing the truth of information are as important as the facts themselves. Second, there is an enormous overload of information and misinformation in the popular media. Information acquired from televised serials and commercials is as likely to be believed as that obtained from documentaries. The majority of incoming college students, for instance, think oil deposits formed from dead dinosaurs. Much of this popular information lacks scientific validation, and its topic matter often deals with "emotional" aspects of life—furry animals and heroic medicine—to the neglect of a broad, holistic view of the living world and its many ramifications for human existence.

The average American's currently distorted view of the living world needs correcting if our society is to make more enlightened decisions on matters involving biology. The popular media are likely to change their emphasis only after the population as a whole has become more sophisticated in its biological awareness. This change will come about only when high school graduates acquire a much clearer perspective on the living world than most people currently possess.

From the multiple biological facts known to scientists and the images of reality they convey, it is necessary to select those that best serve society's needs, as well as the needs of the average individual. Almost all facts have an intrinsic interest for some subset or another of people, and we—the members of the Biological and Health Sciences Panel—trust that the native curiosity of all will be at least partially fulfilled by the topics selected for emphasis here. Our choices have been guided by the following considerations.

The socially overarching need is for citizens in a democracy to take responsibility for their own biological health and to support biologically sound social decisions—as well as to object to biologically shortsighted decisions. This practical goal presupposes a general understanding of Nature and of humankind's place in it, which is the primary and greater goal of teaching biology. The panel's report stresses this latter goal (of understanding), which goes beyond just responsible citizenship and aims to provide everyone with a comfortable familiarity with both the biosphere and the working of the human body.

The curriculum we envision will clearly depart from the usual current catalog of facts, with an occasional experiment thrown in for good measure. Not only will it build concepts as much as possible by using historical and inquiry methods; it will also

apply those concepts to current issues, asking "What does it *mean* to know this?"[1] In this way, biological understanding will become connected in students' minds to questions that are generally labeled "social," "economic," or "ethical."

Biology is not a subject to be learned primarily from books or computerized courses; nor can it be passively acquired from viewing televised programs. It cannot be satisfactorily taught solely within the confines of the classroom even when observation and experiment are emphasized. Understanding biology means being personally in touch with the living biosphere, discovering directly for oneself how it functions. It is only on the framework of personal experience with Nature that classroom lessons can build. Somehow, adventures equivalent to capturing lightning bugs in jars and falling into ponds in search of frogs' eggs need to be incorporated into all our children's experience. There is no substitute for an intimate sense of connectedness and familiarity with the biosphere, and without that sense, biological "facts," no matter how colorfully packaged, will remain dull and conceptually sterile. The panel therefore strongly urges that the biology curriculum encourage personal observation and experiment from the earliest ages. How earthworms move, what happens to flies caught in a refrigerator, how spiders make webs, and the development of germinating seeds should be common knowledge for every youngster—as should the migratory patterns of local birds and the emergence sequence of plant and insect species in the spring. Once their escape from permanent entrapment in an electronic cocoon is assured, students can begin to study biology in a more formal, pedagogically conventional way.

The body of this report consists of a conceptual framework for biology followed by basic biological information. The framework outlines the major themes that should emerge from 12 or 13 years of exposure to the subject matter of biology. The themes, however, are highly abstract and cannot be taught as such. Rather, they should serve as guidelines for curriculum development, so that by the age of 18, most students have an internalized vision of the world and the history of life on it by which they intuitively "know" these things to be so—or very probably so. One's understanding of the passage of energy through an ecosystem, for example, will be as sensible and obvious as the need for wires to bring electricity to one's house and for pipes to remove its wastes.

While the conceptual framework serves as a guideline for curriculum development, the essential "facts" that then follow—the basic biological information—represent the building blocks that gradually form each child's abstract, internalized image of the world of life. In that section of our report, we summarize what seems to us, at this moment, the most essential knowledge, realizing not only that this knowledge, like all knowledge, is subject to emendation but that the informational needs of individuals and society in the future may change the emphasis of what is considered basic.

[1] By "historical method," we mean tracing the historical insights by which scientists have arrived at currently held paradigms, including past instances in which incorrect assumptions (for example, the existence of a homunculus, and the belief that only protein varied enough to encode genetic information) were widely believed by scientists.

billion years ago on a continuous *external* supply of energy-rich organic molecules. The panel believes that everyone should have an awareness of the probable evolutionary steps in energy capture—from an anaerobic broth of organic molecules formed by nonliving processes, to the emergence of self-reproducing "genes" living off these molecules by chemical pathways similar to glycolysis, to the necessity of capturing the energy of sunlight in chemical bonds as the broth was used up, to the ability to use "waste" oxygen as a means of reextracting as needed (through the process of respiration) the chemical energy stored during photosynthesis. Such an awareness provides a mental perspective both on the process of evolution per se as a continual adaptation to new conditions on Earth, and on energy as the primary requirement of life.

The ongoing search for energy has been accomplished, especially in the past billion years, through a remarkable increase in the diversity and complexity of life-forms, particularly of sexually reproducing, multicellular plants and animals. One principle of evolution has thus been the elaboration over time of larger, more complicated species, building upon variants of simpler ancestors. Yet, although most ancestral species have gone extinct or have been replaced by more complex variants better adapted to new conditions, there still exist many simple life-forms such as bacteria and blue-green algae that successfully perform essential functions in the biosphere. The image we gain is of an Earth whose properties are slowly but constantly being changed by the very life-forms it spawns, and whose living communities are becoming ever more diverse and complex. Each new species that evolves provides new opportunities for evolution among other contemporary species, and each is also linked, directly or indirectly, with all other forms of life. Selection for adaptive change, the driving force of evolution, can therefore be read not simply as "fitness for survival," but as "fitting in" with a complex network of diversely functioning organisms.

This perspective of an interwoven community of organisms makes understandable certain aspects of today's Earth that are critical for modern human existence, including our direct dependence on photosynthetic plants for food; our indirect dependence on plants as food or nesting sites of other service-rendering organisms, including those that pollinate flowers, that control pests, and that purify our air and water and maintain soil fertility; the occurrence of atmospheric oxygen and a protective layer of ozone owing to past photosynthesis unaccompanied by an equivalent amount of respiration, which makes terrestrial life possible; and the availability of millions of years of concomitantly stored ancient sunlight in the form of fossil fuels that supply almost all the energy for industrial society, and of which a significant fraction has been consumed in the past half-century.

These properties of Earth are not only essential to our existence; we also threaten each of them in various ways, primarily through careless application of powerful technologies for short-term advantages. A primary goal of the teaching of biology, therefore, should be to clarify the place of humankind in evolutionary time and the position of the human species within the network of living and nonliving forces that make up our planet, and thus to

SECTION 2

A CONCEPTUAL FRAMEWORK FOR BIOLOGY

If we are to meet the goals of familiarizing all adults with the living world on which they depend, of making them feel at home with the workings of their own bodies, and of giving each a sense of humankind's evolutionary place in cosmic time, we shall need to develop a mental vision of reality, a conceptual framework for biology that incorporates several all-pervasive principles. Among these principles are the role of *information* in organizing matter into discrete living and reproducing entities; the need for *energy* to animate and maintain life; and the necessity for adaptive *changes* in organisms to meet new conditions, including changes in other life-forms with which they directly or indirectly interact. Implicit in this framework are the notions of the *reproduction* of individuals and the gradual *evolution* of species through selection of adaptations of their genetically based traits to fit new conditions; the notion of a fairly constant *flow of external energy* that can be captured and is often temporarily stored; and the notion that living organisms are woven together into a complex and interdependent *network of life*—the *biosphere*—a layer only 10 miles thick that encompasses the surface of Earth. Although humans may be the current dominant life-form, they are neither independent of, nor do they have complete control over, other forms of life. Furthermore, the fraction of total energy at work on Earth's surface that humans actually control is minuscule. It is critical for all future citizens to perceive the enormous magnitude of the forces, both physical and biological, that make life on Earth possible and the ways in which human activities threaten the continued smooth functioning of those forces.

Central to our understanding of the biological world is Charles Darwin's concept of evolution, which allows us to envision the history of life from its earliest beginnings to the present day. In presenting evolutionary history, it is appropriate to describe what biologists now think happened, giving the major pieces of evidence as well as pointing out the gaps in the story; and it is also appropriate to point out some of our past errors in telling the story. Current evidence that evolution has indeed occurred—and is occurring—is so strong, however, that although many details remain to be explained, evolution cannot be taught as merely one of a number of plausible explanations for how life came into existence. Indeed, part of the biology curriculum should be devoted to showing how pieces of evidence from such diverse fields as geology, paleontology, plate tectonics, comparative anatomy and physiology, embryology, genetics and molecular biology, population biology, and ecology independently support Darwin's explanation of the evolutionary process.

Intrinsic to this gradual evolution of living forms has been the constant adaptation to new sources of energy as old sources disappeared. With significant exceptions (primarily green plants), living organisms have depended since their origin some three

help restore perspective on our collective actions vis-à vis the environment on which we utterly depend. In particular, a better sense of balance needs to be gained between the "free" services that Nature performs for us and that we destroy at our peril and the expectation that "technological fixes"—in medicine, agriculture, and pollution control—will be invented to save us from the consequences of our ongoing assaults on the biosphere. Some awareness of the powerlessness of humans to retrieve carbon dioxide from the atmosphere, halocarbons from the stratosphere, or pesticides from underground water supplies should be a part of the worldview of high school graduates. The ultimate ecological goal of humankind must be to reestablish an ongoing balance with natural forces, such that the human species, like every other life-form, once again lives *within* its annual income of energy, rather than (as now) exploiting temporary stores of fossil energy and of nonrecyclable minerals, and destroying the biological richness of Earth's soils and the genetic diversity of our millions of fellow species for a temporary, one-time gain in "productive efficiency."

Further, the evolution of the human species offers in itself a representative instance of the complexity of multicellular life-forms—their *reproduction*, the *specialization* of their organs, and their homeostatic *integration*. As one member of a large and familiar group of species, the vertebrates, *Homo sapiens* offers an excellent example of the evolutionary relatedness that occurs among species and of the *adaptive radiation* of ancestral body plans to particular life-styles.

Finally, the evolution of that uniquely human attribute, a conscious and reflecting mind, has given rise to the phenomenon of culture, permitting the overlay of rapid cultural evolution on the much slower process of genetic change. It is culture that has permitted the human species to expand into an enormous range of environments and manipulate them to its own benefit. Such "brainpower," however, also raises a dilemma, since the current population explosion, destruction of environments, and possession of nuclear weapons—all consequences of our species' intellectual prowess—pose threats to continued human survival. The fate of the human species may well depend on all the world's citizens, and certainly those of a technologically powerful country like our own, having the kind of conceptual framework outlined here so that they can participate fully in the wise decisions that will be needed in the future.

To arrive at the conceptual framework outlined above will require familiarity with a considerable amount of basic biological information, which students will need to acquire gradually over a dozen or more years. The mode of teaching, however, should not be directed at their learning specific facts to flesh out the framework, but rather at opening windows for them on facets of the living world—much as Alice stepped through the looking glass to explore Wonderland. Since the wonderland that biology offers is not a dream world but a very real one, it will be all the more rewarding, for it can be explored at will and shared with others.

This basic biological information is organized under four major topics (each corresponding to a section of the report): human

biology, the evolution of diverse life-forms, environmental biology, and human ecology. There is no pedagogical reason, however, for these topics to be taught separately.

SECTION 3

HUMAN BIOLOGY

What information about ourselves is most pertinent if we are to take responsibility for maintaining our own bodies *and* if we are to use our human biology as a model life-form by which to understand our near and more distant relatives on the bush of life? We can pursue this by asking a subset of questions to which we would expect our 18-year-olds to respond in moderate detail.

How Does the Human Organism Work and What Does It Take to Keep It Healthy?

The human body requires a constant influx of energy-rich matter (food) to grow, maintain itself, and reproduce. The multiple jobs of its variously specialized *organs* contribute to one or more of these life processes. Familiarity with the major organ systems of the body can be initiated early by examining one's own anatomy and physiology: observing skin, muscles, joints; measuring blood pressure and pulse rate in relation to exercise; taking one's temperature; digesting starch with one's saliva; testing visual acuity and other perceptive functions; monitoring one's growth rates; examining the nature and properties of blood and urine; and observing and describing the process of wound healing and the way the body recovers from colds and other diseases. In short, students should become familiar with the functions of their own bodies, understand the "vital signs" by which physicians recognize health and disease, and know the roles of diet and exercise in maintaining optimal fitness.

Functions of the internal organ systems will be better understood if the internal organs of another vertebrate dissected by the teacher can be visualized. (This exercise will also underline our evolutionary relatedness to other species.) Thus can students comprehend the role of the elongate digestive tract in processing food, of the lungs (or gills), liver, and kidneys in maintaining *optimal internal conditions*, and of the heart and circulatory system in connecting them all together.

In addition to these "working" organs, there are the "control" organs—the endocrine glands and the nervous system—whose chemical and electrical signals *integrate* the body as a whole. The chemicals of these two systems—*hormones* and *neurotransmitters*—may be either mimicked or antagonized by diverse drugs, medical or otherwise. (Examples include insulin for treating diabetes and amphetamines that mimic the effect of adrenaline in enhancing alertness.)

The human nervous system is a communication system par excellence. The equivalent of an electrical network, it transmits messages between all parts of the body at a speed 10 times faster than a person can sprint. The endocrine system regulates and coordinates at a much slower pace, since its chemical messages pass through the bloodstream to reach their targets. The two systems are integrated in several ways: Nerves can excite some

endocrine glands; some hormones affect brain cells; and the brain itself releases hormones that are intimately related to certain patterns of human behavior. The pituitary gland, located at the base of the brain, is controlled by chemicals emanating from the brain, and in turn regulates such important bodily functions as growth, metabolic rate, and reproduction. Another small gland located within the brain helps regulate the important daily rhythms of our bodies (jet lag is a familiar example of disturbed rhythms).

The role of the sense organs, brain, and musculature in human behavior can be demonstrated through simple physiological studies, as can the limits of the sense organs and the ways we use machines to extend our eyes and ears.

Good nutrition is one of the foremost ways in which each of us can maintain a healthy body. Our basic requirement for calories varies with our genetic endowment, body size, age, and activity. Students should appreciate that all human cells—as well as many other cells—extract energy from energy-rich food molecules by combining them with oxygen. Overall, this process parallels the burning of gas in a stove, since both entail the oxidation of energy-rich molecules to yield water and carbon dioxide. But in a stove, the reaction occurs in a single step, at very high temperatures, and the only forms of energy released are heat and light. In cells, however, *biochemical reactions*, catalyzed by proteins called *enzymes*, release the same energy at body temperature in a sequence of small steps. Only part of the energy is immediately released as heat; the rest is temporarily packaged in special chemicals within the cell that can later be expended to do work. Such work consists of transporting food into the cell and wastes out of the cell; synthesizing new cell components; secreting cell products; or causing cell movements, such as muscle contraction.

More than calories are essential for a good diet; we also need the proper proportions of essential amino acids, unsaturated fats, and vitamins and minerals. Not only should food sources containing these nutrients be identified, but the basic role these nutrients play in the body should be understood (for example, amino acids form proteins; unsaturated fats form cell membranes; B vitamins are needed to assist the enzymes in our cells; and iodine is part of thyroxin, a hormone that regulates our energy metabolism).

The role of nutrition and exercise in maintaining a healthy "heart/lung machine" is equally essential. Obesity and inactivity today kill more Americans than all the infectious diseases combined do. Diet and exercise also play a role in maintaining a healthy digestive system and musculoskeletal system, and in slowing the "diseases" of old age, such as heart disease and stroke—and perhaps also arthritis and cancer. Diet and exercise also provide a psychic sense of well-being.

Other personal behaviors that can damage organ systems are important to know about: the devastating effects of tobacco smoke, breathed firsthand or secondhand, on the lungs and circulatory system; and the multiple effects of alcohol abuse on the liver, muscles, heart, brain, and digestive tract, as well as its effects

on male fertility and on the fetus (induction of fetal alcohol syndrome). The consequences of abuse of other drugs, particularly cocaine and heroin, should be explained in physiological and psychic terms. In addition, the effects of amphetamines, organophosphorus pesticides, hallucinogens, and other substances that are commonly encountered as modifiers of neurotransmission in the nervous system should be understood in broad terms by all students.

The concept of microscopic cells as the fundamental units of all living systems is somewhat more abstract than that of organ systems. But just as each of our various organs performs a specialized set of tasks, so the cells that compose them have diverse shapes to perform diverse jobs. Microscopic observation of cells and tissues will deepen comprehension of body organization through relating architecture to function.

It is at the cellular level that the basic processes of life occur: synthesis, energy conversion, and self-replication, the true hallmark of life. Cells are essentially highly organized chemical "factories," bounded by a fatty bilayer called a *membrane*, and containing many small *organelles* suspended in a watery medium. The "working" molecules of life are *proteins*, long polymers built from 20 kinds of amino acids. Proteins perform many jobs: the structure of hair and bone, the contraction of muscles, the regulation of substances entering and leaving cells, the transport of oxygen, and so forth.

Protein catalysts, or enzymes, are particularly important as facilitators of cellular metabolism, which is the sum of the myriad biochemical reactions that characterize life. Besides the critical processes of photosynthesis and respiration, there are thousands of synthetic and degradative reactions in our cells that underlie all aspects of life. In fact, it is the differences among proteins that determine what life processes an organism can carry out, and hence it is changes in protein function that form the basis for evolution (see below). The function of each protein depends on its specific *shape*, which can be destroyed by heat, acid, or excessive amounts of salt. This accounts for the damage caused to living tissues by burns and dehydration—as well as for the ways we preserve some foods.

Among the several types of organelles found in cells, the *nucleus*, *ribosomes*, and *mitochondria* are essential to know by name. Other organelles are involved in energy storage, or in packaging the proteins the cells export (examples include some hormones, the antibodies, and the digestive enzymes).

The membrane-bound nucleus houses the information-containing *chromosomes*. In this sense, the nucleus acts as the "brain" of the cell. All human cells, at least initially, have a nucleus, as do the cells of other familiar multicellular plants and animals. Nonnucleated cells, such as bacteria, form a distinct class of organisms. Viruses, which consist only of genetic material wrapped in a coat of protein, cannot grow and reproduce except when they have infected bacteria or nucleated cells. Therefore, they are always parasites of their host cells.

Genetic messages from the nucleus are translated on *ribosomes* into the working proteins of the cell. These small protein-synthe-

sizing factories occur in the cytoplasm, mitochondria, and chloroplasts; sometimes they are attached to membranes. It is the cell's ribosomes that viruses parasitize so they can reproduce. *Mitochondria* are small, double-membraned organelles found only in nucleated cells. By means of a sequence of enzyme-catalyzed reactions, they carry out the oxidation of food molecules at body temperature, as described above.

Maintaining our cells and organs in a healthy state also requires a study of health sciences, and the panel believes that the introduction of such a study into precollege biology is long overdue. Students should understand the various sorts of diseases and abnormalities that occur: infectious diseases caused by viruses, bacteria, and animal parasites; metabolic and endocrine disorders; degenerative disorders; cancers; neurological and psychiatric disorders; genetic disorders; and birth defects. In particular, students should acquire some grasp of the functioning of the body's defense system. Natural barriers to invading parasites should be pointed out; these barriers include the skin, tears, saliva, and acidic stomach and vaginal secretions. Proper oral and bodily hygiene can go a long way to promoting good health. Some notion should be gained of the role of white blood cells in immunity, both as active phagocytes for walling off invaders (pus formation) and as producers of specific antibodies or of specific killer cells directed against a particular invader. Although the details of the immune system are extremely complex, every student should understand what happens following a vaccination—that is, what "immunity" is. Students should also be aware of the self/non-self distinction the immune system normally makes.

It is the comprehension of these mechanisms that will help students understand the importance of having their children vaccinated; why the body rejects implanted organs that it sees as foreign, and even the cancer cells that we are all constantly producing; and why the AIDS virus that destroys critical cells of the immune system leaves the body helpless in the face of multiple infectious agents.

Antibiotics, the "wonder drugs" discovered around the time of World War II, are widely used to treat various kinds of infections. But they have also been misused, resulting in the selection and spread of antibiotic-resistant strains of bacteria. Students should know that antibiotics are ineffective against viral infections and that their unnecessary use can be counterproductive in the long run.

The history of our understanding of the causes of infectious diseases, how they are spread, and the body's defenses against them is as interesting as any science-fiction novel. By far the greatest benefits in the conquest of such diseases as plague, tuberculosis, cholera, smallpox, and poliomyelitis have come from preventive medicine (vaccination, water purification, and other public health measures) rather than from corrective medicine (drugs and surgery). Such awareness may help students evaluate where the nation's best interests lie in researching "solutions" to modern killer diseases such as heart disease, cancer, and AIDS.

From Conception to Death. What Are the Main Features of the Biological Life Cycle of Human Beings?

This broad topic comprises everything from human sexuality to the principles of inheritance, and from the mechanisms of cell division to those of molecular biology, which in turn explain the phenomena of growth and development, tissue repair, and aging.

The fascination of young children with their own development (outwardly measured as annual increments of height on the kitchen doorjamb), and with that of baby siblings and pets, permits early inquiry into such matters as where babies come from, how bones grow longer, and why puppies grow up faster than children. Later, children will be ready to learn about their own soon-to-develop sexuality, and from then on the stage is set for completing the more detailed picture of reproduction that follows.

The fact that each of us begins as a single cell, formed by the fusion of an egg and a sperm, leads in two directions—back to where the gametes originated and forward to what the fertilized egg will become. It is natural to begin with the former, since it is less abstract and more closely allied to a child's most immediate concerns about its own maturing body. Thus, students want to know about the internal as well as the external sex organs of both sexes, how their production and release of gametes is hormonally controlled, and the central details of sexual behavior and reproductive physiology (menstruation, pregnancy, birth, and lactation). In particular, the details of the menstrual cycle, and the timing and control of ovulation, are important.

Students should know the various available forms of birth control, their effectiveness, potential side effects, and reversibility; what is involved in abortion; and the several forms of venereal disease and the kinds of treatments, if any, there are for each. As future parents, they should also be informed about common heritable diseases and preventable congenital defects.

We turn next to the cellular aspects of reproduction. Understanding both how gametes are formed and how growth occurs depends on weaving together information on cell structure and chromosomes with the principles of Mendelian inheritance and molecular biology. Genetic information is coded linearly as a sequence of four chemical units (bases) in the DNA of chromosomes. The information is packaged into larger units (consisting of hundreds of bases) called *genes*. Many genes carry the information for synthesizing cell proteins; others regulate this process. When a particular protein is to be synthesized, a copy of its gene is *transcribed*, and then this *message* is linearly *translated* by joining together the specific sequence of amino acids that matches the genetic message. According to this sequence, the completed protein molecule will fold into the definitive shape that gives it its biological function. There is thus a direct correspondence between the linear genetic information in DNA and the final, functional shape of a protein.

Any change in DNA that affects either the information content of a gene or the ease with which the gene is turned on and off (gene regulation) is called a *mutation*. Such changes may arise

as changes in base sequence in chromosomal DNA. Occasionally, foreign pieces of DNA (for example, from viruses) may permanently fuse with chromosomal DNA, causing diseases (herpes, AIDS, and perhaps some cancers). Because mutations may cause "bad" results (such as cancer or genetic defects in offspring), it is important to recognize what stimulates them to occur: mutagenic chemicals, ultraviolet light, and various forms of radioactivity. Some mutations are "silent" or "neutral," but occasionally a mutation may be "beneficial," producing a better adapted organism. (It is on the latter that evolution depends, as is noted below.)

Cellular reproduction is of two kinds. In the asexual reproduction of bacteria, or of human cells during the processes of growth and repair, cells copy themselves during a process called *mitosis*. The chromosomes, which occur in pairs in human cells, one from the father and one from the mother, exactly duplicate themselves and then are carefully separated so that each of the two daughter cells receives a complete and identical set of genetic information. Genetically, eye cells and liver cells from the same person are identical, except for occasional mutations that may have accumulated during the growth process.

In striking contrast are the reproductive cells of sexually reproducing organisms. Through a process known as *meiosis*, eggs and sperm come to possess half the usual number of chromosomes, one of each pair of similar chromosomes found in ordinary cells. (Errors in this halving process—which increase in frequency with age—lead to abnormal numbers of chromosomes in the fertilized egg, causing such diseases as Down's syndrome.) During the cell divisions leading to eggs and sperm, many combinations of maternally and paternally derived chromosomes are possible. Not only are whole chromosomes shuffled randomly among daughter cells, but paired chromosomes may swap pieces, in a process called *crossing-over*, giving rise to even more genetic variability among one individual's eggs or sperm. The number of genetically different offspring a single couple can theoretically produce is astronomical. Sexual reproduction, the reduction divisions of meiosis followed by the union of male and female gametes, occurs among almost all eukaryotes, and even bacteria exchange genetic material occasionally. In each case, it leads to greatly increased variability among offspring, accelerating the rate of evolutionary change. Except for identical twins, each human being is genetically unique.

The study of meiosis and the recombining of genetic information in the union of eggs and sperm in the next (and subsequent) generations makes possible a physical explanation for the laws of inheritance first described by Mendel more than 100 years ago. The discovery of chromosomes and the nature of genes provides a complete historical sequence for understanding the inheritance of discrete traits, the concepts of dominance and recessiveness, the existence of multiple *alleles*, and the reason for independent assortment of some traits and the linkage of others.

Once grasped, this groundwork permits one to understand sex determination and sex-linked inheritance; the concept of "carriers" of various deleterious genes such as those for Tay-Sachs

disease, sickle-cell anemia, and hemophilia; and population genetics, which in turn makes the genetic aspects of evolution comprehensible. (In this context, the genetic relatedness uncovered among human "races" underscores the superficiality of the external traits that are often used to classify groups of humans.) Genetics is an area of biology in which mathematics is particularly helpful in estimating the probabilities of inheriting certain traits and the frequencies of genes in populations, calculating the probabilities of genetic drift in variously sized populations, and in working on other evolutionary modeling problems.

We turn now to the actual process of development. A new human life is set in motion when egg and sperm meet in the oviduct, but an early understanding of development for the young child might better be grasped by observing fertilization and early development in an echinoderm or amphibian embryo. Questions such as "Why do eggs have yolk?" and "How do embryos feed?" lead naturally to the notion of the human placenta and its role in nourishing a developing baby. Observations of the first seven to ten days of chick embryo development can also provide one with a mental image of the unfolding of organ systems—the brain, eyes, heart, limbs, feathers—that have certain parallels in human development.

Since all cells of the developing embryo are genetically the same, the question arises "Why brain in one place and heart in another?" It is the unfolding of developmental processes that most clearly exemplifies the *regulation* of gene expression. We now know that hormones from afar and other molecules produced more locally control the activation of various genes, and that mutations in the control process are as important to evolution as mutations in the genes coding for proteins.

This unfolding process, especially during the early stages of pregnancy, is susceptible to damage from irradiation, drugs, alcohol, and infectious agents such as the rubella virus. Therefore, all potential parents should become familiar with precautions for avoiding such dangers. They should also know about the stages of pregnancy so that they will be able to recognize what is happening; for example, they should know about the occurrence of morning nausea and when to expect the baby's first movements. They should also learn what special health precautions—such as diet, exercise, and the avoidance of tobacco and alcohol—will help to ensure the health of the baby and an easy delivery. (A film of a "natural" birth in which both parents are present and the mother is conscious throughout might be of value in allaying uncertainties about childbirth.)

The basis of milk production, its release during suckling, and its role in inhibiting ovulation are also important to know (although future mothers should be cautioned not to count on lactation alone as a contraceptive). The important socializing bond of breast-feeding and the equally important role of fathers in child care and child rearing are perhaps too easily overlooked in the school curriculum, thereby depriving future parents from making informed choices regarding those critical activities. Knowledge of the physiology of reproduction is also essential for making informed choices regarding contraception, the best age-range in

which to have children, and prenatal diagnostic tests for possible congenital disease.

Our recently acquired knowledge of the genetic code and of the control of gene function has made the engineering of new drugs possible and has increased the potential for overcoming genetic defects and modifying inheritance. New techniques are also constantly appearing for detecting genetic defects before birth or detecting carriers of such defects among future parents. Each of these powerful new technologies, however, raises ethical questions that individuals and societies need to weigh. The people responsible for revising the science curricula for kindergarten through twelfth grade in the years between now and 2061 will want to ensure that this aspect of our advancing knowledge is made an integral part of students' comprehension of the world of biology.

Finally, students in the future are going to be involved more and more with the problems at the other end of the life cycle—those of aging and death. Young adults will be a minority, with both the next generation to care for *and* the preceding ones, as more of their parents' and grandparents' generations survive to near the full human life span.

The biological basis of aging is not well understood. There appears to be for each species, including humans, a *maximum life span*. Although recent advances in medicine, nutrition, and public health have greatly increased the average life expectancy at birth, they have not significantly extended the maximum length of life. Factors that may contribute to the aging process include changes in the immune system, mutations arising and accumulating in cells, the effects of oxidants on cellular constituents, and wear and tear on tissues such as weight-bearing joints. Disorders of the immune system, such as some types of arthritis and endocrine disease, may result in antibodies that destroy the body's own tissues. The immune system also is less able to fight infection as we age, or to protect us against some forms of cancer. Drugs or radiation used in cancer treatment may compromise the immune system further.

Surely 18-year-olds should leave school knowing how at least some infirmities of old age can be slowed. They should be informed about the kinds of care options available for the elderly and the terminally ill, and what social support systems exist. And they should understand the process of dying and death, and the role of overt grieving in the healing process for survivors.

SECTION 4

THE EVOLUTION OF DIVERSE LIFE-FORMS

Earth abounds in a diversity of living creatures, which all interact to some degree. Each type shares properties common to all life, and yet each is different, as a consequence of millions of years of chance evolutionary events. Identifying the differences and tracing their origins provides the mental framework for comprehending the place we humans have in the biosphere, as well as our present impact on it (see Section 6).

How Are Humans Like and Unlike Other Living Organisms?

This question introduces the notion of the unity and diversity of life and helps to place the human species in its evolutionary and environmental context. Before this question can be formally posed, though, children will need to be familiar with as many life-forms as possible, and here we encourage schools to do what today is seldom done: involve the young in their local environment, and help them to observe its natural history firsthand. Children should learn the common names of local plants and animals and be able to identify them to the phylum level. Emphasis should be given to the great diversity of species, even within related groups; there are many kinds of flies, spiders, birds, and so forth, and children should be encouraged to adopt a group as a hobby. A study of pond water or soils can further underline the great diversity of life-forms. Children should equally be encouraged to discover how each life-form "makes its living." It is also important that they understand that life on Earth has had a long history and that many unusual life-forms, now extinct, flourished in the past. Every schoolroom should have several fossils; if local fossil beds occur, students should visit them. This knowledge will be important when, in later years, there is a fuller treatment of ecological interactions and of evolutionary processes. These explorations into the real world can be supplemented by watching documentary nature films. Zoos, natural history museums, and botanic gardens can also help in meeting this goal.

While providing the basis for understanding taxonomy and evolution, this background also alerts students to the complexity of interactions among Earth's biota, giving them a sense of their immersion in and deep dependence on the living biosphere. (Even New York City cannot make do without its green surroundings.) This sense of interconnectedness to all other life-forms can later be demonstrated in more concrete ways. Such broad generalizations as "all life comes from life" can be explained in a scientific way. At the same time, students need to be aware of the variability *within* species, for which the variations within domesticated species provide an example.

Nowhere is the unity—and the grand continuity—of life better exemplified than in the genetic code. The same triplets of bases in DNA and RNA code for the same amino acids, from viruses to humans. There is just *one* genetic language.

A second broadly shared characteristic is that all self-replicating life-forms are composed of cells, from single-celled bacteria and protists to elephants and whales having billions of cells. Although a few giant cells exist that can be seen with the naked eye (for example, the yolk of a hen's egg, and *Acetabularia*), most cells are microscopic and vary little in size. This limit may be due to the fact that cellular reactions depend upon the diffusion of chemicals, including genetic messages from the nucleus to the part of the cell where they are translated into proteins. Although all cells maintain internal currents to supplement diffusion, very large cells are frequently multinucleate (muscle cells) or are supplied by nurturing cells (nerve cells are surrounded by glia).

All cells share not only a small size but also certain fundamental processes. The mechanisms by which DNA is doubled are similar in all living species, as are those for synthesizing proteins. The events occurring in mitosis and meiosis are similar among all organisms with nucleated cells. The same chemical reactions by which human cells obtain energy from the oxidation of organic molecules also occur in other animals, as well as in green plants, fungi, protists, and many bacteria. Not only do organisms use the same genetic language, they also use many of the same genetically coded metabolic pathways. (It is this metabolic similarity that permits us to use laboratory animals as models for studying human diseases and for testing drugs and food additives and screening for environmental pollutants. Unrecognized differences between animal models and humans, however, make direct observations of the effects of these agents on people also essential.)

Yet, while humans clearly share important features with all other life-forms, every child can see that we are more like some organisms than others. Understanding the levels of human kinship to primates, other mammals, and vertebrates generally underlines our evolutionary connectedness, and introduces the notion of adaptive radiation. Why, for example, do seals have flippers? What happened to the arms and legs of snakes?

In classifying organisms, biologists for many years drew the main divisions according to how energy was obtained. Photosynthetic green plants (called self-feeders, or *autotrophs*) were the province of botanists, and food-consuming animals (called other-feeders, or *heterotrophs*) were studied by zoologists. In thinking about the flow of energy through ecosystems, this is still a useful dichotomy. More recently, however, organisms have been grouped in another major way, according to whether they are simple cells without nuclei, called *prokaryotes*, or more complex cells with nuclei, called *eukaryotes*. This dichotomy has major evolutionary significance and, moreover, is likely to become a matter of common parlance as genetically engineered prokaryotes are developed to produce new chemicals, to control pollution, and to modify crop plants.

The most common and important organisms that are enormously different from ourselves are the green plants on whose photosynthetic abilities our lives depend, and their biology should be familiar to all. In particular, everyone should firmly grasp the ability of the green pigment chlorophyll, located in complex membrane-bound organelles called *chloroplasts*, to trap selected

colors of sunlight and use that energy to synthesize energy-rich sugars from the energy-poor molecules, carbon dioxide and water. In essence, plants are able to take carbon dioxide and water, plus the ashes in the fireplace, and resynthesize the log you just burned, at the same time returning to the atmosphere the oxygen consumed in the fire. *It is upon this remarkable property of green plants that almost all life today depends.*

The various organs of green plants are useful to us in many ways, so it is important to know the parts of plants and their functions as organs. Having no true skeletal system, plants rely on heavy cell walls, made of cellulose, to give them shape. This is the same cellulose we use for bulk in our diet, for cotton and linen fibers, and for fuel and building materials and paper. The water and nutrients that plants take up from the soil by their roots flow upward in tubes to the leaves, where they are converted to sugars and other small molecules. These energy-rich compounds then flow by way of another set of tubes throughout the plant. The sap of sugar maples and the latex from rubber trees are two forms of these nutrient rich fluids that humans have learned to exploit.

Having roots means staying put. Unlike animals, most plants depend upon wind or pollinators to help them mate, and upon wind or fruit- and seed-eaters to disperse their seeds. Students should be able to distinguish the functions—for the plant—of the nutrients in seeds (for nurturing the germinating embryo) and in the fruit (for attracting dispersers). In this context, it is less important to know the parts of a flower or the names of the layers of a seed coat than it is to understand the functions of pollen, nectar, colored petals, and fruits in maintaining the life cycle of plants. Surely, planting vegetable seeds, tending the sprouting embryos, and harvesting the fruits or other edible parts should be part of the experience of every child.

Students would benefit from observing special adaptations of native plants to the local climate, since such knowledge (like that of the adaptations of animals mentioned above) paves the way for an understanding of evolution. Most young people will be interested in useful products produced by plants: preservatives such as creosote, and solvents such as turpentine; insecticides such as pyrethrin; various oils and resins; and innumerable medicines, from the precursor of aspirin to morphine and curare. They may want to note ways in which plants store nutrients, as in bulbs, tubers, seeds, and so forth, and perhaps to explore little-used local plants as potential sources of food.

How Do New Species Arise?

The grand synthesis of all our similarities and differences vis-à-vis other organisms is found in the concept of the evolution of species. The notion of *species* is intuitive rather than precise, for, like all our definitions, it depends upon the presumption of sharp boundaries where in fact the boundaries are vague. For practical purposes, a species comprises all similar organisms that could potentially interbreed.

But are individuals that mate in captivity but never in the wild the same species? How do we define those bacterial "species"

whose individuals clone themselves and never mate at all? Yet it is this very vagueness that makes the evolution of one species from another, or of two or more species from a common ancestor, so natural a process—a process that continues today. On a human time-scale, evolution is a slow and almost imperceptible process, and when we look at two slightly different populations, we are never quite sure just where they are in the speciation process.

Darwin's concept of the evolution of species rests on three observations: most organisms regularly produce more offspring than the environment can support; their offspring vary genetically (owing, as we now know, to mutations and to sexual recombination); the offspring best adapted to their surroundings are most likely to survive. By this process of *natural selection*, a gradual change in the genetic constitution of a population will occur and the "more favored" new species will replace the "less favored" old one.

There is no field of modern biology that does not lend support to this idea, and we should assume that all educated people are familiar with Darwin's reasoning. It "makes sense" of comparative anatomy and embryology and of the homologies of form and function; it is substantiated by the evidence in the fossil record; and the unity of the DNA code and our understanding of the mechanisms of mutations and their molecular consequences for genetics and modern molecular biology (examples of which are mentioned above) all support and expand Darwin's theory.

All students should be familiar with this evidence and have a sense of the history of life through the ages. Although we do not (and may *never*) know exactly how life in fact originated, several quite plausible theories have been proposed for the spontaneous formation of complex molecules on primitive Earth and for their gradual coalescence into reproducing entities. Fossil evidence indicates that life has probably existed for three billion years, during the first two billion of which there were only prokaryotes. With the advent of sexually reproducing eukaryotes, there was a great burst in the rate of evolution, with the emergence of increasingly complex organisms. Our earliest human ancestors did not appear until about five million years ago, however. Humans are thus very recent newcomers on the evolutionary scene.

Although most earlier species have gone extinct, or have been supplanted by newer forms, among the "survivors" are some of the most ancient species known—certain bacteria and blue-green algae. The simple amoebas, seaweeds, sponges, and corals have survived hundreds of millions of years. Thus, evolution is not merely a "ladder," by which "lower" forms are automatically replaced by "higher" forms, with humans emerging at the "top" by right of their "advanced" state of development. Rather, evolution is like a bush, with many branches emerging long ago; some branches have died out, some have survived relatively little changed over time, and some have repeatedly branched, giving rise to sequentially more complex organisms. All extant species interact in the living web we call the biosphere.

Students should be aware of the many unsolved problems in evolutionary biology and of some of the procedures used to seek answers. The concept of evolution is also a fine place to introduce the difference between scientific and nonscientific explanations, in this case for the origin of life and its change over time.

SECTION 5

ENVIRONMENTAL BIOLOGY

The biosphere *is* our home, and as such it deserves understanding in its own right. To feel "at home" in it requires the same familiarity with the way it works that we have about the house we live in. The more we understand about our surroundings, the closer our attachment to them and the greater our sense of "belonging." Modern industrial society has tended to estrange itself from the natural world, treating it as something alien—to be shunned, tamed, or exploited. Before we can adjust the human behaviors that now threaten the planet, however, we have to adjust our attitudes toward that planet, and doing so requires a friendly familiarity with the ways in which it functions.

Much of the preparation needed to understand how the environment functions will have been laid in the early years, if the recommendations in the preceding sections are pursued. Students will have gained an intuitive notion of the concept of species. The community of organisms is not a continuum of diversity (there are no cat-dogs, as far as we know); rather, each organism is a member of a group of structurally and functionally similar individuals—a species. The members of a species have the same ecological niche (way of life), and are more or less restricted to a particular habitat and geographic range; the males and females do not hybridize with members of other species.

Students will also have begun to put organisms not only into kinship (taxonomic) categories based on structural similarities but also into functional categories based on ways of making a living. There are animals that live off plants, and then there are animals that live off other animals. Bees and hummingbirds, a long way apart in the taxonomic scale, both feed on nectar—and thereby fortuitously pollinate flowers. Similarly, mice and sparrows may eat—and thereby accidentally disperse—the same seeds, although no one would mistake one species for the other.

Both the similarities seen in kinship relations and the divergence of clearly related forms that have become adapted to different life-styles *(adaptive radiation)* provide support for the notion of natural selection as a process. So too does the occasional remarkable *convergence* in form of two quite distantly related species—the shark and the porpoise, for instance—adapted to the same habitat and way of making a living. When students have made these kinds of observations, they will readily perceive that organisms have been selected to "fit" particular habitats and life-styles.

As young people pursue their observations of plants and animals, they should be asking not only "How is this organism adapted to making its particular kind of living?" but also "How do its activities affect its environment, including other species?" and "What is its *function* in the ecosystem?" Their early encounters with the diversity of organisms should thus lead to an understanding of the differences in life strategies between green plants (autotrophs) and all other organisms (heterotrophs), and

of the differences among predation, parasitism, and saprovory. On the basis of this approach, students can begin to see the interrelations among species and to perceive that groups of sometimes quite unrelated species perform similar functions. Thus they can begin to organize the complex parts of ecosystems into integrated wholes.

How Do Green Plants Feed Earth's Inhabitants?

It is easy to memorize the statement that all life depends on green plants; but unless the meaning behind the statement has been carefully thought through and assimilated, it conveys no more information than that C follows B in the alphabet. The central concept of ecology is that life is maintained by the continuing throughput of energy from the sun and by the repeated recycling of the atoms that make up the molecules of living organisms: carbon, oxygen, hydrogen, nitrogen, sulfur, phosphorus, calcium, potassium, and so on. The biosphere as a whole is a closed system in terms of matter, and it is driven by sunlight. This is a fairly sophisticated concept to grasp, however, and it only makes sense when one has gained an understanding of the *functions* of the organisms at various *trophic levels* and how each interrelates with the others. Only then can the systems approach be conceptualized.

Perceiving that green plants (autotrophs) feed Earth means perceiving that all other organisms (heterotrophs) rely on an *unbroken flow* of energy-rich organic molecules that ultimately were synthesized by green plants. Students will want to practice tracing the flow of matter/energy back down the food chain, thus becoming familiar with some of the functional roles played by various organisms in the ecosystem. A human eating a trout, for example, relies on the fact that the trout ate mosquitoes that fed on rabbits that ate the leaves and roots of plants. Furthermore, this is a decremental chain; only a small fraction of food consumed at each trophic level goes to building body mass, the rest being consumed for maintenance. This puts a limit to the length of food chains—and makes it clear that some human foods are far more "sunlight-expensive" than others.

In natural ecosystems, very little of the sunlight that is captured in energy-rich molecules is "wasted"; some organism or other consumes it. Particularly important are the saprovores, or decomposers, whose role in completing the recycling of mineral nutrients is crucial but seldom appreciated. (Our failure to completely recycle the organic wastes of farms and cities is depleting the land of its fertility.) An important exception to the rule that no sunlight is wasted occurred millions of years ago during the Carboniferous period, when the role of photosynthesis exceeded the recycling ability of decomposers; dead fern trees accumulated, creating the great coal beds, and dead organisms in shallow seas were compressed into oil. The fossil fuels that run our economy consist in effect of 100-million-year-old sunlight. The rate at which sunlight is being stored today, in peat bogs and in oil-forming sites in the ocean, is insignificant compared to our role of consumption; hence, it is evident that we are living off the past.

What Determines the Productivity of an Ecosystem?

Ecosystems are shaped by climate (light, temperature, and rainfall) and the availability of soil nutrients; together, these factors determine what kinds of plants can live where, and how much photosynthesis they can carry out. The world has a diversity of physical conditions, creating the freshwater and oceanic domains and the familiar terrestrial biomes, such as forests, deserts, and grasslands. Given that humans now exploit almost all corners of Earth, familiarity with the major kinds of ecosystems and the factors limiting their productivity will help students understand, among other things, why temperate-zone agriculture cannot be transported to the wet tropics or to the Arctic, and why the open oceans will never yield the fish catch already being exploited near coastlines.

Overall productivity is determined by the rate of photosynthesis in an ecosystem. Students should understand that in general the total productivity of natural ecosystems almost always exceeds that of agricultural systems. (The main exception is in irrigated arid regions.) Among the most productive ecosystems in the world are coral reefs and tropical rain forests. At the present rate of decimation, however, the rain forests will be gone by the year 2061, resulting not only in the loss of thousands of species but also perhaps in changes in local and even global climates.

Why Are Most Natural Ecosystems Fairly Stable Over Long Periods of Time?

Although an attack of insects or a prolonged drought can decimate a nation's crops, such phenomena seldom threaten natural ecosystems, and even when catastrophes such as fires occur, the system slowly but surely undergoes *succession* back to its original state. This stability (sometimes called "equilibrium" by ecologists) is a remarkable and important property. Although agricultural systems, by their very nature, are far from being in equilibrium, an awareness of factors contributing to stability might help the nation move toward a less vulnerable, as well as more sustainable, agriculture (see below).

Ecological stability is a complex matter, and the forces creating it are multiple and difficult to quantify. Nevertheless, certain principles emerge. Sudden, temporary swings in climatic conditions—unusual drought or abnormal cold—may affect a few sensitive species in an ecosystem, but the dominant types of organisms survive. Most natural species have a margin of tolerance. A similar principle applies when one species—a competitor, predator, or parasite—threatens the extinction of another through a sudden increase in its population. Quite often, a third species proliferates to control the threatening species. Populations of different organisms thus appear to be held within certain limits by their interactions with other species.

Such regulation leads to the concept of the *carrying capacity* of the environment for a particular species. It is a concept important to grasp since it applies to *Homo sapiens* as much as to any other species. It implies—as Darwin had observed while on the *Beagle*—that the natural tendency of a population to

increase geometrically is held in check by one environmental factor or more: lack of food or nesting sites; competition with other species for similar resources; predation; or infestation with parasites. (Not only animals but also plants are susceptible to parasites, as well as to predators, and some have evolved structural and chemical means of defense against both.) Any species that overshoots the carrying capacity of its environment, owing to a temporary imbalance between resources and checks, eventually undergoes a crash, bringing it back into balance. So relevant is this principle to the present explosion of the human population that it seems to us of the first importance that all Americans—indeed, that all citizens of Earth—should comprehend the principle.

SECTION 6

HUMAN ECOLOGY

Understanding the relationships between the human population and its life-supporting environment is surely essential for everyone. Despite our total dependence on the environment, human activities today are putting our environmental support system at risk. Several things are different about today's environmental degradation compared to that of the past. First, the human population, having doubled nearly three times in the past century, is now pushing Earth's resources to their limits. Second, the consumption of global resources, being extremely polarized between the one-fifth of fairly rich people and the four-fifths of admittedly poor people, gives rise both to severe local environmental destruction and to political and economic instabilities. Third, unless sustainable forms of energy are harnessed, industrial nations will be unable to maintain their current levels of production and consumption. Fourth, the extraordinarily rapid rate of change of everything (population, pollution, prices of commodities, interest rates, technologies, governments, and so forth) further destabilizes social institutions locally and globally.

All American citizens should grasp these facts. Accepting them depends upon understanding the physical and biological limits that Nature places on us. We believe that these problems, now rarely dealt with in a substantial manner in the classroom, have become so critical that they must form a key part of education, extending biological awareness into the study of social sciences, history, and even literature.

How Is the Continued Sustainability of the Ecosystems on Which We Depend Related to the Amount of Available Energy—Over and Above the Sunlight They Need for Photosynthesis?

The material wealth generated by human economic systems is constrained by the same laws that natural ecosystems obey. Sustained economic productivity is absolutely linked to a throughput of energy sufficient not only to synthesize *new* products (be they trees, crops, or automobiles, etc.) but also to completely recycle the *old* (dead leaves, human sewage, industrial and agricultural wastes, household garbage, etc.). When the available energy is insufficient, the ecosystem draws upon its capital reserves, thereby depleting them (as in soil leaching and erosion, and depletion of mineral reserves). At the same time, the unrecycled matter accumulates as pollutants (of air, water, and soil) that further decrease ecosystem (economic) productivity. Only when the energy available is sufficient for *both* tasks are ecosystems (and economic systems) sustainable indefinitely. Probably no country in the world today, however, is living on a currently sustainable basis.

All natural ecosystems (with one or two minor exceptions) rely solely on the annual income of sunlight that they capture as

useful energy through the photosynthetic activities of green plants and on secondary solar services such as rainfall and climate. Until approximately two centuries ago, all human economic systems did the same. If they exceeded their natural support system or if the climate changed, then the local environment was destroyed, and the population either migrated or changed its life-style and declined in numbers. Many developing countries rely almost entirely on sunlight for all their energy, and almost everywhere forests are being depleted, soils are being eroded, and deserts and wastelands are expanding as populations exceed their energy income and hence their environment's carrying capacity.

Although population densities are often lower in industrial countries, their per capita energy consumption is 10 to 20 times higher and is obtained *not* from the constant flux of today's sunlight but from sunlight that has literally been buried in the ground for hundreds of millions of years in the undecayed, energy-rich molecules of primeval fern trees (coal) and small aquatic organisms (oil and natural gas). This represents one-time capital from the past; what took millions of years to accumulate will be used up forever in another two centuries, and the "pinch" is already being felt. Solar energy, wind, wood, and hydropower represent a sustainable energy income from the sun. All people should realize that our entire industrial wealth is 90 percent dependent upon a temporary energy source. They should further realize that even our present massive energy consumption falls far short of what is necessary to complete the recycling of wastes, so that neither plant nutrients nor industrial raw materials are being replenished; rather, they are accumulating as pollutants (discussed below).

By What Processes Are Resources Recycled?

Much confusion exists regarding "renewable" and "nonrenewable" resources. Students should know that energy is *never* renewable; the same energy cannot be made to do work twice. Sunlight is often (mistakenly) called "renewable" because it flows nonstop, whether we trap it for useful work or not. What *can* be used over and over is matter—atoms and molecules. What counts in recycling such things as, for example, water, nitrogen, oxygen, iron, or tin, is the energy needed to *concentrate* them in sufficient quantity and *convert* them into useful forms. Left to themselves, things spontaneously tend to mix together randomly. This tendency, known as *entropy*, is reversed only by doing the work needed to separate, concentrate, and purify. The laws of thermodynamics tell us the minimum amount of energy required to achieve a particular concentration of a dispersed substance.

Natural cycles, called *biogeochemical cycles*, exist that utilize, directly or indirectly, the diffuse but constant energy of sunlight to convert and concentrate (or purify) the substances necessary for life. Fresh water merely requires heat from the sun to purify it by evaporation from the oceans; when it condenses, gravity concentrates it into lakes and streams. Oxygen and nitrogen in useful forms are provided by the activities of plants and microorganisms, respectively. The photosynthetic concentration of

diffusely distributed carbon dioxide and conversion of the gas into energy-rich organic carbon in the leaves of plants is one of the most extraordinary recycling phenomena known. Destruction of organisms involved in natural recycling interferes with this renewal process, as when forests are removed or when toxic wastes kill microorganisms in soil and water. Contamination of recycled substances with pollutants also decreases or destroys their usefulness, as when groundwater or sewage are contaminated with toxic industrial effluents. When biogeochemical cycles are disrupted, the ability of an ecosystem to support life is diminished, and energy is required to correct the problem.

So-called "nonrenewable" resources are those for which there is no natural resupply process that is rapid enough to keep up with the rate of resource depletion; these are millennia-long geological processes. By adding extra energy, of course, humans can concentrate and purify nonrenewable resources. The entropy laws, however, tell us that the energy is not trivial, and that no technology can overcome the minimum energy required. Oceans contain thousands of times the gold in Fort Knox, but no one "mines" them; the energy cost would be prohibitive. The remarkable success of natural cycles rests on their ability to capture the massive amounts of diffuse sunlight reaching Earth and the long time periods available.

It is thus to be hoped that young people will leave school with a sense of the distribution of Earth's resources; of the projections of future supplies; and of possible substitutes for scarce nonrenewables; and with a sense of responsibility to future generations to conserve what is left.

How Does Accumulating Pollution Affect Humankind's Future?

The unrecycled wastes of industrial society seriously erode both environmental and human health. We are producing carbon dioxide, sewage, and similar "nontoxic" wastes at rates greater than natural cycles can absorb them. We also are releasing toxic, often nonbiodegradable, wastes in ever-greater quantities that are accumulating in soil, air, and water. The consequences are that we are damaging the natural environment (for example, forests damaged by acid rain and smog), our agricultural systems (for example, crops ruined by soil degradation and air and water pollutants), and human health (for example, pesticide residues on food, indoor air pollution from synthetic polymers, outdoor smog, contaminated drinking water, and toxic waste dumps under homes and schools). In the coming years, it is likely that the epidemiology of pollution will be of growing concern. Therefore, students should become familiar with the major kinds of pollutants, their sources, their effects, and the still unpaid costs of cleaning them up.

In addition to their immediate impacts on ourselves and our surroundings, our pollutants may be creating long-term climate changes. It is especially important that young people know about the potential "greenhouse effect" resulting from the buildup of carbon dioxide and other human-made gases, and of the continuing destruction of the stratospheric ozone shield by Freon and

other compounds used in air conditioning and refrigeration, airplane exhausts, and the massive use of fertilizers. Deforestation and desertification also affect local climates and may have global consequences. In this respect, students should be informed of the possible global climatic consequences of a nuclear holocaust ("nuclear winter") and their likely impact on the entire biosphere. (This information will supplement their general understanding of the direct physiological consequences of exposure to ionizing radiation: from radiation sickness, to increased cancer rates, to a rise in genetic disease in future generations.)

What Ecological Considerations Are Necessary for a Sustainable Agriculture?

Over the past 10,000 years, most human beings have come to depend on agriculture to sustain them. Students should be aware of this history—of why different techniques have been used in various times and places (such as shifting agriculture, dry and irrigated farming, "high" farming, and modern mechanized monoculture), and of the constraints on crop species imposed by different climates and soils. They will need some knowledge of the historic selection of domesticated species and of their current genetic manipulation. And finally, they should learn the ecological meaning of "sustainability" by contrasting the 5,000-year continuous productivity of the Nile river valley with the potential decline of certain kinds of modern agriculture.

Today, both European and American agriculture have non-sustainable aspects—of which the greatest is erosion, which may partly be ameliorated by no-tillage farming. This, however, usually requires heavy application of herbicides. Failure to recycle nutrients removed at harvest requires the addition of synthetic fertilizers that frequently contaminate groundwater supplies. In some areas, groundwater for irrigation is being overdrafted, eventually leading to dry farming, with greatly reduced yields. Monoculture of certain crops, such as rice and cotton, requires heavy pesticide application to prevent unchecked predation; pesticides also contaminate water supplies.

Agricultural science in the future is likely to take several new directions. In addition to the use of bioengineered pest-resistant and drought-tolerant crop plants and vaccines for healthier animals, more sustainable farming techniques are likely to be introduced. These techniques may include no-tillage farming; more perennial and mixed agriculture; the substitution of locally adapted wild plants (such as leguminous trees) and animals (such as buffalo and other game) for current domesticates; improved knowledge of soils and of pest-management techniques; and increased recycling of natural soil nutrients. And perhaps today's seed banks, now falling behind in conserving disappearing plant species, will be expanded and new techniques will be developed to preserve animal germ plasm. Yet, students should be aware that seed banks are a poor substitute for naturally growing plants and animals; while stored, germ plasm is in an evolutionary limbo, unable to adapt to a changing world. A better long-term strategy is to preserve the natural ecosystems still remaining.

A final note of caution is needed regarding the introduction of new species, whether from abroad or newly "engineered," into an ecosystem. So poor is our understanding of ecosystem stability that seemingly innocuous introductions of species in the past have sometimes had catastrophic consequences. Examples include rabbits and prickly pear cactus in Australia; mongooses in Jamaica; sea lampreys in the Great Lakes; and the wild gooseberry in North America's white pine forests. We should therefore proceed cautiously when intentionally introducing new species into ecosystems, especially into our oversimplified agricultural ecosystems.

SECTION 7

CONCLUSION

The study of biology, which must be approached as a long-term and continuing enterprise for all the citizens of a democratic society, should be directed toward the realization of two principal objectives. First, one must understand biology to understand oneself as a product of evolution and as but a single entity embedded in a broad ecological scheme. Human biology and human ecology thus are critical focal points for the student of biology. Second, the study of biology teaches rules to live by. These rules encompass the full spectrum of human behaviors—how we treat our bodies and those of others and how we treat the environment we depend on. Our biological knowledge helps us to make sound decisions on health and diet practices as well as on economic issues.

The principal theme running through our proposed biological sciences curriculum, therefore, is the central role that knowledge of biology must play if the electorate of a democratic society is to make proper choices about the optimal ways of leading one's own life and directing the broader course of society. Although biology is fascinating for its own sake and offers enormous aesthetic rewards for its students, the full rewards of a well-thought-out biology curriculum include those that serve the society that cares enough to foster an excellent educational system.

APPENDIX

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NOTICE

This is one of five panel reports that have been prepared as part of the first phase of Project 2061, a long-term, multiphase undertaking of the American Association for the Advancement of Science designed to help reform science, mathematics, and technology education in the United States.

The five panel reports are:

- *Biological and Health Sciences: Report of the Project 2061 Phase I Biological and Health Sciences Panel*, by Mary Clark
- *Mathematics: Report of the Project 2061 Phase I Mathematics Panel*, by David Blackwell and Leon Henkin
- *Physical and Information Sciences and Engineering: Report of the Project 2061 Phase I Physical and Information Sciences and Engineering Panel*, by George Bugliarello
- *Social and Behavioral Sciences: Report of the Project 2061 Phase I Social and Behavioral Sciences Panel*, by Mortimer Appley and Winifred B. Maher
- *Technology: Report of the Project 2061 Phase I Technology Panel*, by James R. Johnson

In addition, there is an overview report, entitled *Science for All Americans*, which has been prepared by the AAAS Project 2061 staff in consultation with the National Council on Science and Technology Education.

For information on ordering all six reports, please contact Project 2061, the American Association for the Advancement of Science, 1333 H Street NW, Washington, D.C. 20005.